Efficient and high performing hydraulic systems in mobile machines

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Abstract

Hydraulic systems represent a crucial part of the drivetrain of mobile machines. The most important drivers of current developments, increasing energy efficiency and productivity, are leading to certain trends in technology. On a subsystem level, working hydraulics are utilizing effects by improving control functions and by maximum usage of energy recovery potential. Independent metering and displacement control, partly in combination with hybrid concepts, are the dominating approaches. Traction drives gain advantage from optimized power split transmissions, which consequently are being used in a growing number of applications. On the level of components, increase of efficiency and dynamics as well as power density are important trends. Altogether, design of systems and components is more and more based on modular concepts. In this sense, among others, sensors and control elements are being integrated to actuators; electric and hydraulic technology is being merged. In order to achieve maximum efficiency and performance of the entire machine, control of hydraulics has to include the whole drivetrain and the entire mobile machine in its application. In modern words, mobile hydraulic systems are a part of cyber physical systems.

KEYWORDS: mobile hydraulics, efficiency, productivity, independent metering, displacement control, power split transmission, electro-hydraulic drives

1. Mobile drivetrain systems development

Development of hydraulic systems and components for mobile machines takes place in an environment which is continuously looking for improvements. The need to reduce CO_2 emissions and resource consumption leads to a must of efficiency increase. But additionally, the gain of efficiency has to be utilized for the increase of productivity. On the other hand, especially in order to reach higher efficiency and productivity, the product environment changes into so called Cyber Physical Systems (**figure 1**) /1/ /2/ /3/. That means process, drive, machine, electronic control, machine network, the world wide web and the whole information and communication technology have to be taken into account when developing hydraulics today. Hence people are talking about the Internet of Things. In this sense the hydraulic system in mobile machines has to be considered and has to be developed as a primary subsystem of the Internet of Things.

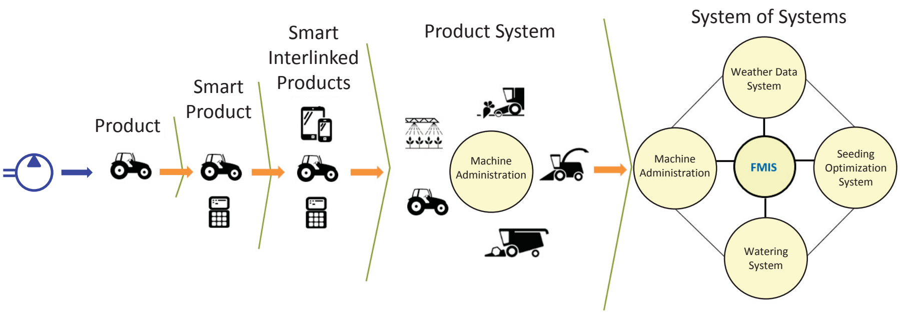

Figure 1: The Internet of Things in agriculture (/1/ /2/ adapted)

In today's mobile machines, the internal combustion engine (ICE) is the most important prime mover. Since efficiency of these units is strongly dependent on the operating point in terms of speed and torque, one major goal of drivetrain layout and operating strategies is to keep the ICE close to its best operating point. This has been subject to recent research projects /4/ /5/ and is also part of current product releases and development (e. g. Danfoss Best Point Control /6/). The offering of speed variable transmissions to new applications e. g. based on hydro-mechanical power split concepts (Grimme Vario Drive /7/) also points in this direction. Especially on tractor-driven mobile machines, the development of comprehensive drivetrain management systems is an upcoming challenge, because communication and system knowledge has to overcome manufacturer's borders. Up to now, CAN is the standard for communication, offered to agriculture implements by ISOBUS. At least if mobile drivetrain systems will get more open to other technologies (prepared by AEF) or if new control architectures of subsystems (e. g. independent metering) require more complex information, alternative structures of communication might be considered.

2. Hydraulic subsystems and components

As major subsystems of mobile drivetrains, working hydraulics as well as traction drives have to be in focus for maximizing efficiency.

With working hydraulics, reduction or avoidance of metering losses and energy recovery represent the most important development goals. Both researchers and manufacturers investigate several approaches in parallel. Based on valves, independent metering is to be regarded as a key measure, offering a wide range of possible architectures /8/ (**figure 2**). One crucial challenge is to ensure controllability under dynamic working loads, which requires fast acting valve mechanics and instantaneous processing of the load condition information. Latest developments that are commercially available act either with hydro-mechanical /9/ or with direct electro-hydraulic flow control /10/.

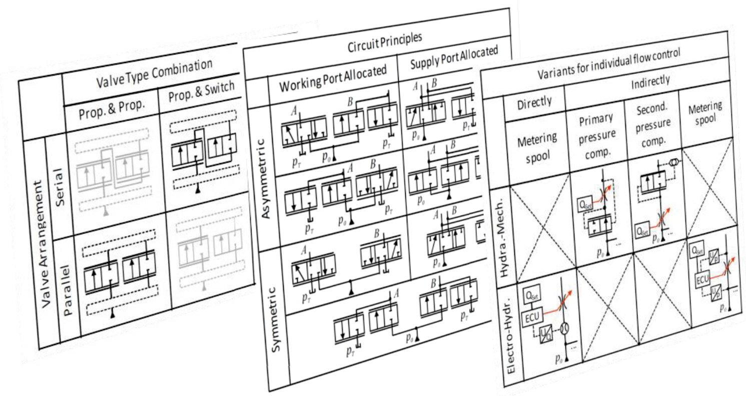

Figure 2: Structuring of independent metering control architectures (/8/ adapted)

Full displacement control on mobile machines must include asymmetric motors, which consequently have been a major aspect of research work since many years /11/ /12/ /13/. In any case, continuous control of differential cylinders requires additional individual control elements. Multi-pump concepts (primary / flow control) show good potential, especially for construction machinery with a typically high power rating of single actuators that must be supplied at the same time. Constant pressure (secondary control, hydraulic transformer) represents an option and has to be taken into account for systems with a broad range of medium power, consecutively actuated motors.

While the effect of reducing losses out of the control architecture is a general one, raising the efficiency potential from energy recuperation is strongly dependent on the present application /14/. Implementation of hydraulic hybrid systems, using accumulators on one or two constant pressure levels /15/ /5/ (**figure 3**) have proven good results, especially when recuperation potential is comparatively low.

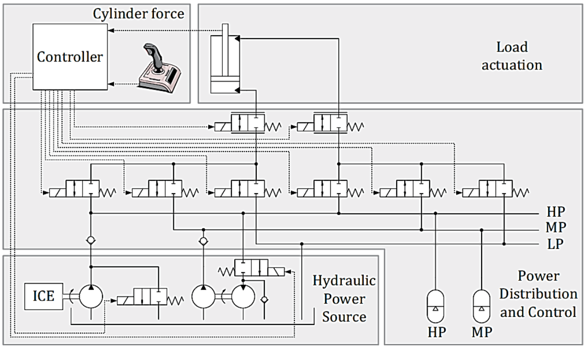

Figure 3: Independent metering system with additional pressure level: STEAM /5/

Traction drives are more and more becoming hydro-mechanical power split drives in all applications. On the hydrostatic path including the control level, innovations are made by integrating new functions to the drive unit in order to reduce the number of mechanical clutches to a minimum. By also minimizing the share of circulating power, efficiency is being further increased. Significant features of recent developments are (multi-)coupled planetary gears as well as a change of pump/motor operation of one displacement machine /16/. Thus, latest power split transmissions often are so-called compound solutions. Implementation of a third machine is either used for hydrostatic power distribution on different drive axles /17/ (**figure 4**) or within a concept of partially full hydrostatic power transmission /18/.

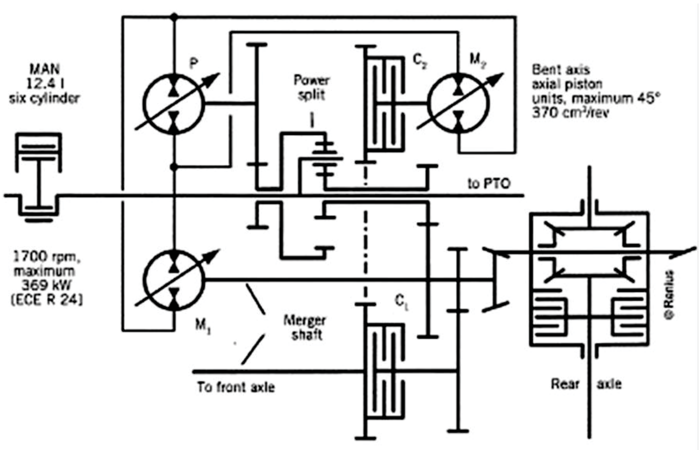

Figure 4: Hydro-mechanical power split, Fendt VarioDrive /17/

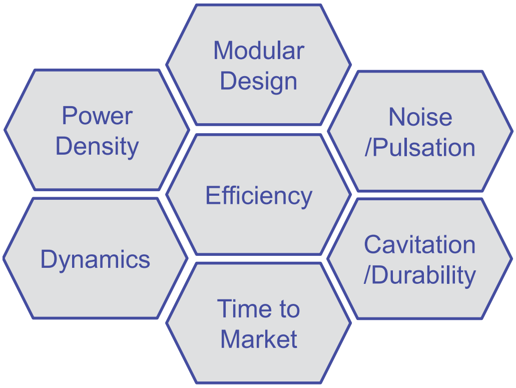

Figure 5: General requirements for hydraulic components

For hydrostatic components, the system and subsystem development try to fulfil a considerable set of requirements including high power density, minimum losses and maximum dynamics (**figure 5**). This is especially true for hydrostatic displacement machines. Dry case operation of bent axis axial piston machines has proven suitable in order to avoid churning losses and with this, increase speed /19/. Another approach to higher power density is reducing installation space, e. g. by compensation of inner forces. Linde showed this by means of a swashplate coupled double motor that produces significantly less radial bearing forces and allows higher speed /20/ (**figure 6**).

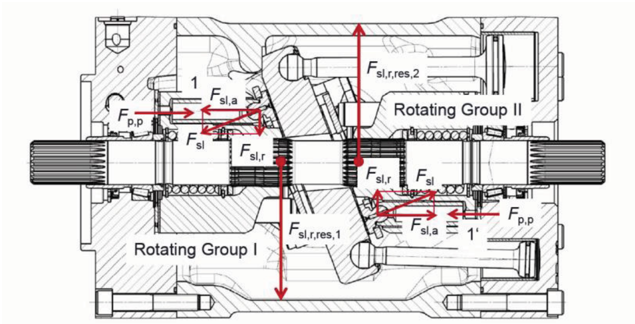

Figure 6: Cut away view of the Linde HMV105D double motor /20/

In addition to directly power-related aspects, NVH-performance, modular design and time to market are drivers of recent developments (figure 5). CFD development methods are in favour of investigations concerning cavitation and with this, also contribute to improving power density /21/ (**figure 7**). The same applies to modelling air separation behaviour, e. g in hydraulic tanks /22/ /23/ (figure 7). Due to TCOrequirements and tight installation space on machines with Tier 4 engines and exhaust treatment systems, the fluid reservoir on mobile machines is getting smaller, which affects its de-aeration function. Active measures of air separation have recently been put into product for stationary applications /24/.

Especially with valves and cylinders, modular design concepts and functional integrations are being developed that allow easy combining of different dimensions and control concepts in one system (e. g. /25/) and provide integrated sensors /26/. A recently presented concept of valve-cylinder and sensor integration /27/ demonstrates all aspects of modular system design and distributed control, supplied by hydraulic power bus and interlinked via CAN.

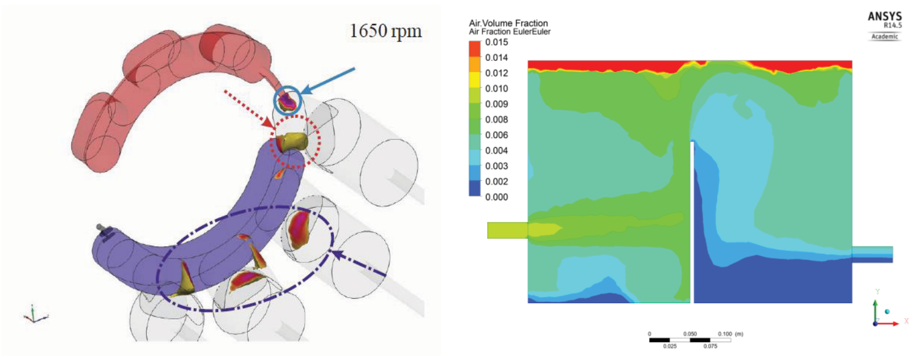

Figure 7: Cavitation critical areas on piston pump /21/ (left side), CFD simulation of multi-phase flow in hydraulic tank /22/ (right side)

On the hydraulic supply side integrated sensors and data bus linkage on displacement machines are almost standard and part of the modular concept. Development potential exists in the field of auxiliary low pressure applications, such as charge and feeding pumps or cooling circuits (**figure 8**). Here, different approaches are being investigated and put into products, ranging from switch-off solutions to variable pressure by means of valve or displacement control /28/ /29/. Depending on the system architecture, secondary displacement control may also prove suitable, as recently presented for a hydrostatic fan drive /30/.

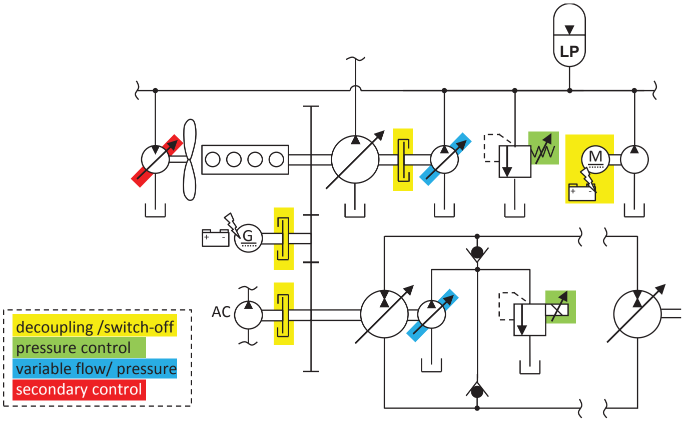

Figure 8: Examples of efficiency measures on mobile low pressure hydraulics

3. Comprehensive solutions and future development

As stated before, the development environment of mobile hydraulic subsystems is the entire drivetrain system of the mobile machine and the system beyond. Hence, efficiency improvements and a reduced number of drivetrain components can be achieved by solving functions hydraulically that have been parts of other technical domains before. For example it was shown by Linde, that synchronization of drive shafts for shifting in transmissions can be managed by pure control of an existing variable displacement machine /31/. The same applies to hydrostatic start-stop systems /32/ /33/ (**figure 9**), which are providing even better acceleration performance than standard electric starters.

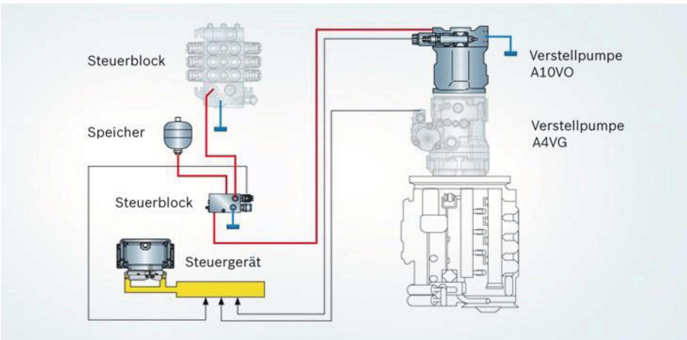

Figure 9: Hydraulic start-stop system for construction machinery /32/

As motion and load characteristics of working hydraulics differ from the respective characteristics of traction drives in many applications, additional synergies in drivetrain concepts may be gained from a combination of these major subsystems. Using energy recovery potential of one subsystem for supplying the other has already proven concept /14/, either with direct feed-through (as far as possible) or use of energy storage (accumulator) in between. Supplying a closed circuit traction drive and asymmetric working hydraulics out of a single primary displacement unit imposes one step further in system integration /34/ (**figure 10**). As the supply in this newly proposed system is meant to work at higher average power and with this at better efficiency, the approach should be of advantage even if energy recovery potential is low in the respective application. Thus, the challenge in control regarding hard- and software is at least as high as with standalone independent metering.

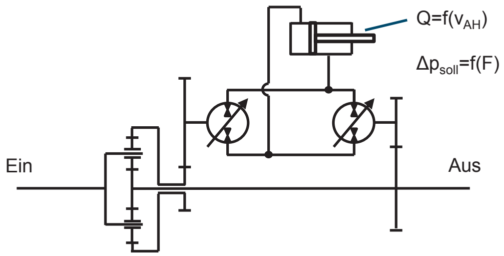

Figure 10: Concept of integrated working hydraulic and traction drive /34/

System integration by means of trans-disciplinary technology approaches is required by fully electrified mobile machines (**figure 11**). Mostly due to the benefit of zero local emissions, they are emerging in different new applications, e. g. in construction and agriculture.

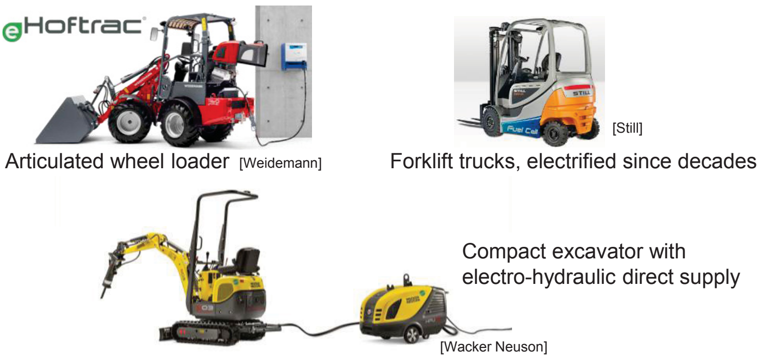

Figure 11: Examples of electrified machines /37/ /38/ /39/

However, positive features of electro-hydraulic actuators, such as high precision, controllability and zero power losses in standby are not exclusive to upcoming electric vehicles. In fact, electro-hydraulic steering /35/ introduces hydraulics to new applications, for example trailer systems. On the supply side, electro-hydraulic concepts typically imply flow control by shaft speed, which can also work as a suitable efficiency measure in classic hydraulic drives. As a further approach, the efficiency potential of a two-pump supply including a connection to the electric power system on a common mobile machine is currently being investigated /36/.

Summing up current and accomplished developments, main conclusions on a future trend are as follows:

Development of more energy efficient system architectures is ongoing. Because of the vast variety of load cycles and individual requirements of mobile machines, methods for application oriented assessment and layout of driveline systems are essential. Power supply on demand is a main aspect of systems efficiency as well as energy recovery—if possible.

Future development of mobile hydraulics is drivetrain system development. This means, getting maximum performance out of a diesel engine as well as taking maximum advantage out of an electric prime mover. Both concepts require simple intelligent solutions on a component and subsystem level, interlinked to control networks and open for being applied to new machine functions. Thus, mobile hydraulic systems are part of cyber physical systems, implying a trans-disciplinary way of thinking.

In addition to this brief proceedings paper the presented charts are available. Send an e-mail to: imn@tu-bs.de.

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